Evidence for asteroidal origin of the Tunguska object

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Abstract. The progress in the understanding of the Tunguska object is reviewed in the light of evidence presented in numerous recent investigations, which appeared following the publication of my 1983 paper on the object's proposed asteroidal nature. The issues addressed extensively in the present review involve: (i) the fundamental characteristics of the event, such as the object's energy, altitude, and velocity at the time of its terminal explosion and the dynamic pressure involved; (ii) the problem of atmospheric fragmentation of very massive impactors and the implications for their ablation and deceleration; (iii) new analysis of the orientation of the Tunguska object's heliocentric orbit based on the best data on the apparent radiant of the fireball's atmospheric trajectory; and (iv) comparison with the findings of other recent investigations, including compositional studies. Also employed in the arguments are the results now available on the impacts of comet Shoemaker - Levy 9's fragments into Jupiter and the findings of a recent comparative study of two huge fireballs (one cometary, one stony, both involving impactors several meters across) observed with the cameras of the European Network of fireball monitoring. It is concluded that hypotheses based on presumed cometary origin of the Tunguska object encounter unsurmountable difficulties and that the interpretation of the event as a fall of a small stony or carbonaceous asteroid is not only plausible but virtually certain.

1. Introduction

Two great cosmic events that occurred during the 20th century are certain to remain topics of continuing scientific debates for a long time: the impact of the Tunguska object in Siberia on June 30, 1908 and the collision of Comet Shoemaker-Levy 9 with Jupiter in July 1994. The first episode is dwarfed by the latter when measured by the amount of released energy. On the other hand, the Tunguska event directly involves the issue of a threat to our civilization. Scientifically, information on either event is priceless. One advantage that we now enjoy is that, together with the recorded and analyzed instances of great fireballs penetrating the Earth's atmosphere, the Jovian collision provides us with an opportunity to examine the effects caused by the Tunguska fall by comparing them with interpolated, rather than extrapolated, effects of other events,

A major objective of this review' is to show that we are now essentially ready to address the solution to the perennial problem on the nature of the Tunguska object, even though some minor questions still remain. The characteristics of the event and the properties of the involved object, known from the limited evidence available, can be evaluated in terms of the criteria that are currently considered to be most diagnostic for asteroidal and cometary origin. Comparison with impactors whose origin can more straightforwardly be assessed is probably the most appropriate avenue in pursuing this task.

In compliance with this philosophy, I address below only the most symptomatic aspects of the problem. To **some** degree, this work is an extension of my previous investigation (Sekanina 1983, referred to heretofore as Paper 1), where the conclusion on the object's asteroidal (stony or carbonaceous) nature was based on an analogy between the characteristics of the Tunguska event and a number of less massive fireballs with terminal flares. The fundamental argument was that a comet of the mass estimated for Tunguska could not possibly survive an aerodynamic pressure of anywhere near 2000 bars, which it should have been subjected to, if its pre-explosion velocity were ~30 km/s. Further arguments, developed below in the light of the results by other researchers, complement and reinforce the conclusion of Paper 1.

2. Known properties of the Tunguska fireball

The fundamental physical characteristics of the Tunguska event were summarized in Table I of Paper 1. Some of their most accurate determinations came from investigations of seismic information. In particular, the explosion energy was found to amount to 5×10^{23} ergs by Ben -

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Menahem (1975) from his analysis of seismic records from several stations, a value that within a factor of two was confirmed by at least three studies based, respectively, on the data on an overpressure that caused the forest devastation, on timing of the magnetic-field disturbance, and on amplitudes of the atmospheric waves. Additional independent investigations led to energy values that are on the same order of magnitude.

The next critical characteristic is the explosion altitude. From the time delay of the Rayleigh waves relative to the SH body waves, Ben-Menahem (1975) obtained an altitude of 8.5 km. Independent results, between 5 and 12 km, were published by at least seven other researchers.

Of particular interest are the attempts to estimate the fireball's velocity immediately preceding the explosion. Referring to the finding by McDonald and Goforth (1969) that the ballistic wave associated with a sonic boom continues to move with the pre-explosion velocity of the source, Ben-Menahem (1975) concluded that a velocity of 7.5 km/s offered the best fit to the seismic observations he analyzed. This result is in excellent correspondence with the velocity range of 7–8 km/s that Zotkin and Tsikulin (1966) obtained from their laboratory simulation of the uprooted forest, the only other velocity determination that is not strongly model dependent.

Combining Ben-Menahem's numbers for the explosion energy and pre-explosion velocity, one finds that a mass of 1.8 million tons was involved. This result is in satisfactory agreement, within a factor of two, with a much more uncertain mass determination by Fesenkov (1949), based on his analysis of the anomalous extinction of solar light in the atmosphere for several weeks after the fall. Also, it is not inconsistent with Ganapathy's (1983) estimate for the object's total (i.e., entry) mass inferred from his detection of the iridium spike in ice samples from the Antarctica, which he found to coincide with the event. Unfortunately, this last evidence has been refuted by Rocchia *et al.* (1990), who detected no contribution in the ice-core samples, but set no strict constraints on the mass from their iridium measurements. Fesenkov (1949) referred his estimate to the object's *initial*, preatmospheric mass, but a fraction of the entry mass should have vaporized and thus would not have contributed to the detected extinction effect caused by particulates suspended in the atmosphere. As discussed below, in the framework of an asteroidal hypothesis this is not a critical point, because the preatmospheric and terminal masses of the Tunguska object are not expected to have differed by more than a factor of several.

Other characteristics of the Tunguska event that will be utilized in this paper are the time of fall, the geographic coordinates of the epicenter of the point of explosion, and the coordinates of the fireball's apparent radiant in the sky. The time of explosion, 0:17:28 UT on June 30, 1908, is known with high accuracy from the seismic records (Ben-Menahem 1975). The best coordinates of the explosion's epicenter appear to be determined from the extensive mapping of the region of devastated forest, including the patterns of uprooted trees (Fast *et al.* 1976, 1983), which also is the most reliable source of information on the azimuth of the fireball's trajectory. These issues are discussed in Sec. 5.

3. Impact events that bracket the explosion energy of the Tunguska event

Circumstances of the impacts of the nuclei of comet Shoemaker–Levy 9 into Jupiter are still hotly debated in the literature. For the most complete compendium of information and for current trends in the data analysis and interpretation, the reader is referred to a recent book of review chapters on this event edited by Noll *et al.* (1996). The explosion energies of the major fragments are found to have been generally on the order of 10^{27} ergs, which is up to 10^4 times the Tunguska's explosion energy (Sec. 2). It should be remembered, however, that the explosion energies of the nuclei of Shoemaker–Levy 9 were only minor fractions of their initial kinetic energies (before they entered the Jovian atmosphere), while the Tunguska's explosion energy could have been a more significant fraction of its preatmospheric energy. The reason for this will become more apparent from the following.

In spite of some controversial aspects of the interpretation of the nature of Shoemaker–Levy 9, one fundamental issue of major interest from the standpoint of Tunguska studies has been essentially resolved: Shoemaker–Levy 9 was indeed a comet (whether active or inert) and not a stony asteroid. The primary reason for this conclusion is not the object's appearance, even though each fragment was surrounded by a coma and displayed a tail. Indeed, there is evidence that these features could have been products of the process of tidal breakup near Jupiter in early July 1992 rather than signs of activity. It is, instead, the occurrence of the tidal breakup itself that points to the parent object's very poor coherence and is symptomatic of its cometary nature. Even at the time of closest approach, about 25,000 km above the planet's cloud tops, the Jovian tidal forces were entirely inadequate to disrupt, or to assist in disrupting, a stony object. On the other hand, dynamical simulations of the body as a self-gravitating *strengthless* assemblage of small building blocks of refractory material have indicated that the aggregate's tidal breakup and its subsequent partial collapse into a fairly small number of discrete clumps of debris could occur only if the object's initial bulk density was ~ 0.5 g/cm^3 (e.g., Solem 1995, Asphaug and Benz 1996). Since a cometary nucleus possesses some limited tensile strength, all models that approximate it as a strengthless agglomerate are unphysical, but they offer an *upper limit* to its true bulk density. This is therefore an important constraint which, in addition to the established extreme brittleness, implies for the object a bulk density **entirely** outside the realm of plausible values for stony asteroids (~2-4 g/cm^3).

Appropriate comparison objects with explosion energies lower than Tunguska's are provided by the most massive and brightest fireballs detected photographically by the various fireball networks. The great advantage of these data is that they contain high-quality information on the orbits of the objects and fairly good estimates for their initial and terminal masses. Available information on a total of 14 objects larger than 1 m in diameter, whose atmospheric motions had been photographed prior to 1992, was conveniently summarized by Ceplecha (1 994). Two additional objects belonging to this group, tile Peckskill meteorite (Brown *et al.* 1994, Beech *et al.* 1 995) and the Marshall Islands fireball (McCord *et al.* 1995, Tagliaferri *et al.* 1995) were detected more recently.

In order to demonstrate the relevance and importance of massive-fireball investigations, 1 refer to tile results of a recent study by Borovička and Spurný (1 996) of two extremely bright fireballs detected by the European Network. Their results represent a dramatic illustration]] of differences in the behavior of the two impactors during their atmospheric flight, thus depicting the immense structural discrepancies between extremely "soft" material, unquestionably of cometary origin, represented by the Šumava fireball, and "hard", stony material, exemplified by the Benešov fireball.

Borovička and Spurný first determined the orbits and light curves of the two objects and showed that the peak panchromatic magnitudes, normalized to a distance of 100 km were - 21.5 for Šumava and - 19.5 for Benešov, with an uncertainty of ±1 mag in either case. The preatmospheric masses for the two objects were estimated by these authors at, respectively, 5 and 13 metric tons, which, with the accurately determined entry velocities, imply the initial kinetic energies of 1.8 and 2.9 x 10^{19} erg, about 4 orders of magnitude lower than the explosion energy of the Tunguska object. This is about where the similarities between the two fireballs end. Before discussing the implications of Borovička and Spurný's results, I list the differences between the two fireballs that are relevant to the present topic:

(i) Šumava's luminous trail began at 99 km, where the dynamic pressure reached ~2 mbar and the atmospheric pressure was merely 0.4 μbar; this was more than 8 km higher than the beginning of Benešov's luminous trail;

(ii) the rate of Šumava's brightening in the early part of the trajectory was considerably steeper, so that at an altitude of ~75 km above sea level it was already intrinsically brighter than Benešov by about 12 magnitudes;

(iii) the discrepancy between the terminal altitudes of the two fireballs was immense: Šumava left no luminous trail below an altitude of 59 km, where the dynamic pressure was near 1 bar and the atmospheric pressure 0.25 mbar; Benešov, on the other hand, was subjected to dynamic pressures of up to 90 bars (that is, two orders of magnitude higher than Šumava) and was visible down to an altitude of ~17 km, where the atmospheric pressure was near 90 mbars;

(iv) the fireballs' deceleration profiles likewise differed dramatically from each other; Šumava's atmospheric velocity decreased by only about 3 km/s, or ~10 percent of its initial velocity, between the altitudes of 99 km arid 61 km, just before its complete disintegration; by contrast, Benešov began to decelerate substantially at an altitude of about 35 km and its velocity decreased by more than 16 km/s, or more than 75 percent of its initial velocity at 91 km, by the time it penetrated down to an altitude of 19 km;

(V) the light curves of the two fireballs were as dissimilar as they could possibly be: Šumava displayed a series of extremely brief flares (<0.1 s in duration), with the fireball's normalized brightness exceeding magnitude - 20 during its three most prominent outbursts but reaching only magnitude - 10 during its minor terminal flare; by contrast, Benešov was brightening more steadily, it underwent a number of flares of moderate amplitude, all of which occurred at altitudes below 45 km, and its brightness peaked near the end of its luminous trail during a huge terminal explosion;

(vi) even though the flares of both fireballs clearly correlated with discrete fragmentation events, the altitudes of the most prominent ones were 76, 74, 70, and 67 km for Šumava, but 42, 33, 31, and 24 km for Benešov, illustrating another major distinction between the two objects; in addition, the trajectories of several individual fragments of Benešov were directly observed, providing evidence for their sizable dimensions; for Šumava, on the other hand, no fragments were detected and a trial-alld-error analysis of the light curve led Borovička arid Spurný (1996) to the conclusion that ~95 percent of the lost mass immediately disintegrated into microscopic particles;

(vii) while fragmentation was important during the atmospheric flight of either object, the implication is that the two fireballs experienced grossly different patterns of mass ablation: whereas significant fractions of Benešov's main body and sizable fragments were losing their mass gradually during atmospheric flight through thermal ablation, characterized by an ablation coefficient σ of ~0.01 s^2/km^2 or less, Šumava, for which the bulk density and the effective value of σ were found to be, respectively, 0.1 g/cm^3 and 0.32 s^2/km2 lost almost one half of its preatmospheric mass in the most powerful, extremely brief outburst at an altitude of 67 km and additional 40 percent of its mass in the other three major outbursts; nearly all of the remaining 14 percent was lost by quasi-continuous fragmentation between the flares, with the contribution from thermal ablation being entirely negligible;

(viii) Borovička and Spurný conclude that the Šumava fireball disintegrated *completely* at an altitude of 59 km above sea level, while the terminal mass of Benešov although not recovered is estimated at about 3 kg.

4. Atmospheric fragmentation and the terminal explosions

The classical meteor theory is based on the single-body model, which neglects fragmentation, even though its occurrence in meteors has been recognized for a long time. The first systematic investigation of progressive meteor fragmentation was conducted by Jacchia (1955) in connection with his analysis of the so-called *faint-meteor anomaly*, which was very strongly pronounced on Super-Schmidt photographs of meteors, especially of shower meteors (such as the Giacobinids, i.e., meteors of unquestionably cometary origin). The peculiarities listed by Jacchia for these meteors, whose typical preatmospheric masses were in the subgram range, can be summarized as follows:

(i) the observed deceleration increases much faster than predicted by a single-body theory, implying extraordinarily high rates of mass loss;

(ii) the initial part of the light curve is somewhat irregular and extremely steep, with the intrinsic brightness increasing often a couple of magnitudes in less than 0.1 s, but there are no major flares;

(iii) the shutter breaks become progressively more obliterated along the photographed trajectory until they disappear entirely, leading to a virtually continuous trail; when this transition, usually referred to as *terminal blending*, occurs rather abruptly, it is always accompanied by a sudden drop in the velocity.

I list Jacchia's diagnostic signatures of meteor fragmentation in detail, because with one readily understood exception there are startling similarities between his description of these phenomena in subgram particles and their account by Borovička and Spurný (1996) in the Šumava object, whose preatmospheric mass was *seven* orders of magnitude greater. Indeed, one of Borovička and Spurný's figures shows that a single-body theory (their Model A) overestimates the velocity at altitudes below ~65 km, consistent with Jacchia's primary fragmentation signature. Next, in the early part of Šumava's trajectory, in the altitude range from 84 km down to 76 km, the fireball's intrinsic brightness is found by Borovička and Spurný to have climbed, somewhat irregularly, at an average rate of about 20 mag/s, again very close to what Jacchia concluded for the Super-Schmidt meteors. And, finally, Borovička and Spurný state specifically that the shutter breaks are completely blurred toward the end of the trajectory, in perfect correspondence with Jacchia's third fragmentation signature. The only exception is that, unlike the small Super-Schmidt meteors, the Šumava fireball displayed major flares in the second half of its light curve. The absence of such flares is the faint meteors is unquestionably due to the fact that fragmentation rapidly consumes nearly all their mass, with no appreciable residual mass left to trigger such flares. A major conclusion based on the listed similarities between the faint meteors and the Šumava fireball is that *the fragmentation signatures are, except for the flares, essentially independent of the impactor's mass.*

Turning to the Benešov fireball, the application of the single-body theory was now found by Borovička and Spurný to be more appropriate, so that the comparison with the behavior of faint meteors is substantially less favorable. In particular, the shutter breaks of both the main body to the point of its first breakup and of several of its fragments up to the end of their trajectories were easily recognizable and for three fragments the measurements could successfully be analyzed by methods of the single-body theory. Also, Benešov's light curve in the upper part of its trajectory was very smooth and the rate of brightening much less steep than for Šumava. The obvious conclusion from these comparisons is that *fragmentation of Benešov was substantially less severe than fragmentation of Šumava* and that the mode of fragmentation was different for the two objects: *most of Šumava's mass disintegrated abruptly into microscopic debris in a few isolated events, while Benešov was primarily breaking up into discrete, major fragments that continued to ablate.* The fairly successful application of the single-body theory to some of Benešov's fragments implies that the role of fragmentation relative to melting and evaporation in this impactor's ablation process was not nearly as dominant as it was in the case of Šumava.

Even though Borovička and Spurný (1996) are by no means the first ones to emphasize the dominant role of fragmentation in the ablation of fireballs, their results offer an extremely compelling illustration of the fragmentation effects. The authors show that the process of fragmentation depends critically on the impactor's *structure*; they clearly distinguish between quasi-continuous fragmentation and what I prefer to call discrete-event fragmentation; and they introduce a simple, but powerful concept of destruction depth to facilitate the numerical modelling of the discrete events. Borovička and Spurný thus contribute significantly to the understanding of atmospheric fragmentation of massive fireballs, expanding the results of the earlier investigations, such as those by McCrosky and Ceplecha (1970), by Grigoryan (1976, 1979), by Novikov *et al.* (1984a, b), and by Ceplecha *et al.* (1993), to list a few. However, it should be remarked that only the techniques by Ceplecha *et al.* and by Borovička and Spurný address not only the quasi-continuous mode but also the discrete-event mode of fragmentation. It should also be noted with much regret that the majority of the investigators of the Shoemaker-Levy 9 impact events failed to account for atmospheric fragmentation altogether, which inevitably resulted in gross errors of the explosion altitudes and initial masses of the comet's fragments (e.g., Mac Low and Zahnle 1994, Zahnle and Mac Low 1994).

In the first approximation, it is unnecessary to apply any elaborate technique to account for fragmentation of a fireball. In the field of meteor physics it is well known (e.g., Ceplecha *et al.* 1993) that effects of quasi-continuous fragmentation can effectively be incorporated in the ablation coefficient, which is inversely proportional to the specific heat of ablation. If $Q_{\rm evap}$, $Q_{\rm melt}$, and $Q_{\rm frgm}$ are, respectively, the specific heats of evaporation and melting and the energy required for breaking off a unit mass by fragmentation, an "effective" ablation coefficient $\sigma_{\rm eff}$ is approximately

$$\sigma_{\rm eff} \approx \frac{\Lambda_{\rm evap}}{Q_{\rm evap}} + \frac{\Lambda_{\rm melt}}{Q_{\rm melt}} + \frac{\Lambda_{\rm frgm}}{Q_{\rm frgm}}, \qquad (1)$$

where $\Lambda_{\rm evap}$, $\Lambda_{\rm melt}$, and $\Lambda_{\rm frgm}$ are the corresponding efficiency coefficients. Analysis of observations of massive fireballs shows that for many of them, especially the brittle ones, of cometary origin, the last term on the right-hand side totally dominates, because $Q_{\rm frgm} \ll (Q_{\rm evap}, Q_{\rm melt})$; this of course is the essence of the statement, that *atmospheric fragmentation of such impactors should under no circumstances be neglected.*

The results of Borovička and Spurný's (1996) analysis of the Šumava fireball allow one to make important inferences on the relationship between discrete-event fragmentation and quasi-continuous fragmentation. Comparison of their three ablation models for the fireball shows that the value of the ablation coefficient can always be adjusted so that all mass has completely been ablated by the time the termination point of the light curve is reached, When it comes to the terminal-altitude determination, the virtual equivalence of the two modes of fragmentation can be illustrated by Borovička and Spurný's application of their discrete-event fragmentation model for Šumava to the nuclei of comet Shoemaker-Levy 9. The terminal altitude, some 40 km above the 1-bar level that the two authors derive, practically coincides for objects of the same size and bulk density with the results of Sekanina (1993), which were based on the quasi-continuous fragmentation approximation (cf. Sec. 7 for more comments).

Even though this approximation matches the terminal altitude, Borovička and Spurný show that neither the fireball's deceleration profile nor its light curve can be satisfied by such solutions. Nevertheless, it is significant that the effective ablation coefficient σ that the two authors find for Šumava, $0.32\ {\rm s}^2/{\rm km}^2$, is comparable with if not somewhat higher than the characteristic value of σ proposed by Ceplecha and McCrosky (1976) in their classification for the IIIb group of cometary fireballs of considerably smaller masses. This result confirms that *fragmentation of cometary objects does not become less important as their mass increases* and that its significance may in fact be even more dominant for subkilometer-sized and larger comets. Together with Borovička and Spurný's indication that ablation of very massive fireballs by fragmentation clearly *precedes* the deceleration of the main residual mass, the implied scenario shows that *prolific fragmentation of a "soft" impactor of cometary nature necessarily allows only a small fraction of the preatmospheric mass and therefore a small fraction of the preatmospheric energy to participate in the terminal explosion*, if any residual mass is at all available for this explosion. Indeed, Borovička and Spurný show that Šumava's luminous flight through the Earth's atmosphere was terminated by only a minor flare that probably involved a mass of about 12 kg, or some 0.2 percent of the object's initial mass. This means that Šumava was not a sufficiently massive cometary object to generate a prominent terminal explosion.

Evidence from the collisions of the nuclei of comet Shoemaker-Levy 9 with Jupiter offers a picture that is consistent with this conclusion. In particular, it is well known that the observed ejecta plumes were generated during the explosions of only the most massive among the impactors. There is no doubt that the less massive nuclei produced ejecta plumes of their own, but too little mass was involved to be detected. As already mentioned in Sec. 3, the explosion energies responsible for the most spectacular plumes have been estimated at up to a few times 10^{27} ergs, so that the involved masses were close to 10^{14} g. The residual mass in a plume may have contained one or a few percent of the preatmospheric mass, considering that the largest nuclei were up to 4 km in diameter arid almost 10^{16} g in mass, as derived from their images taken with the Hubble Space Telescope prior to their impacts (Sekanina 1995).

It therefore appears that the mass of a precipitously fragmenting cometary impactor that enters the atmosphere of a planet, such as the Earth or Jupiter, apparently needs to be more than 10^{14} g in order to trigger a powerful explosion near the end of its trajectory. Less massive cometary impactors dissipate the mass erratically during their atmospheric flight, ending up with no appreciable mass at low altitudes. By contrast, a number of fireballs observed by both the European and the Prairie Networks, of estimated initial masses as small as 10'1 g were observed to exhibit major terminal flares. Their light curves were displayed in Paper 1, where it was shown that this category of fireballs was dominated by the members of the Ceplecha McCrosky's (1976) classification type II, usually associated with objects of carbonaceous chondritic composition. It also was shown in Paper 1 that, the critical aerodynamic pressure $P_{\rm E}$ at which the type II fireballs explode is a slowly varying function of their entry mass and that the value of $P_{\rm E}$ for the Tunguska object should have been ~200 bars, with an estimated uncertainty of ±30 percent. At an altitude of ~8 km, this dynamic pressure implies a pre-explosion velocity of about 8 km/s, in excellent agreement with the results by Zotkin and Tsikulin (1966) and by Ben-Menahem (1975). Because objects of the Tunguska size are not efficiently decelerated in the atmosphere prior to their terminal explosion, the low pre-explosion velocity strongly implies a preatmospheric velocity that only marginally exceeded the velocity of escape, as is typical for asteroids that circle the Sun in low-eccentricity, low-inclination orbits. This result corroborates the fireball's pre-explosion mass of 10^{12} g (Sec. 2). With fragmentation of a stony object far less severe than in the case of a comet, a fairly large fraction (perhaps as much as a few tens of percent) of the Tunguska object's initial mass should have survived atmospheric flight until the time of terminal explosion. Hence, the mass of microscopic dust that contaminated the Earth's atmosphere was probably a few times 10^{12} g, an amount which is consistent with Ganapathy's (1983) independent estimate and which apparently is tolerable in that it caused major continent-wide, but not global, atmospheric extinction and scattering effects.

To postulate the cometary hypothesis for the Tunguska object now becomes mute, because the pre-explosion velocity could not be explained. Even without this fatal flaw, there would be other difficulties with the object's cometary origin. Because of the prolific mass dissipation due to precipitous fragmentation, the fireball's entry mass would have been a few times 10^{13} g or more, an amount at least one order of magnitude greater than for a stony object. The contamination of the Earth's atmosphere by microscopic dust would have been correspondingly more severe and could trigger extinction effects approaching proportions of a truly global catastrophe.

As if all these shortcomings already were not enough, the Earth's collision with a comet ten or more times as massive as a stony asteroid would be an event much less likely for at least three reasons: (i) in the near-Earth environment, the population of comets is strongly depressed in comparison with that of asteroids; (ii) the spatial density of all interplanetary objects, on which the probability of a collision with the Earth depends, decreases with increasing mass; and (iii) the Earth's capture cross section reaches its maximum for objects in low-eccentricity, low-inclination orbits. Some of these points were already made briefly in Paper 1; they present profound statistical arguments against Tunguska having been a comet.

In summary, fragmentation as the ablation process whose effects strongly discriminate between cometary and asteroidal fireballs points unequivocally to asteroidal nature of the Tunguska object. To some, this evidence may already be compelling enough. For those who remain unconvinced, additional arguments below employ evidence that is entirely independent and based on orbital information. Yet, the reader will see that the verdict is the same.

5. Orientation of the heliocentric orbit

Only one of the Tunguska object's three orbital elements that determine the orientation of its heliocentric orbit in space is known with very high accuracy. This is the direction of the nodal line, determined by the time of fall and characterized by the longitude of the ascending node, which is equal to $\Omega = 279°.075$ for the standard equinox of J2000.0. The other two angular elements determining the orbit's orientation in space are entangled with the perihelion distance and the orbital eccentricity through the four quantities: the heliocentric distance at the node r_Ω, the azimuth A_R (reckoned in this paper from the geographic north through the east) and the elevation h_R (or the zenith distance z_R) of the apparent radiant, and the preatmospheric velocity. Of these, the best determined is the nodal distance, $r_\Omega = 1.0168$ AU, followed by the radiant azimuth.

Relatively little attention has over the years been paid to arguments for either origin of the Tunguska object based on constraints in the orientation of its heliocentric orbit. The fireball's time of fall and the general direction of its atmospheric motion was interpreted independently by Zotkin (1969) and by Kresák (1978) as evidence for the object's association with the β Taurid daylight meteor stream and therefore with Periodic Comet Encke. Even though this hypothesis gained, in its time, some favorable publicity in the scientific community, even a cursory inspection shows that the arguments it is based on are flimsy. I showed in Paper 1 that the presumption of the Tunguska object being a fragment of Encke's comet is unacceptable unless the difference of 56° between the orientation of the object's and the comet's nodal lines is explained, which it is not by either of the two proponents. Their comparison of the Tunguska object with the β Taurids is invalid, because small meteoroids in a 10^{-4} g range that are detected by radar techniques to make up this shower experience much greater nongravitational perturbations in interplanetary space than do massive bodies of the Tunguska size.

The absence of basic orbital similarity between the Tunguska object and the short-period comets of Jupiter's family was argued in Paper 1 on a plot of aphelion distance versus the angle that the line of apsides makes with Jupiter's orbital plane. Yet, Levin and Bronshten (1986) considered the object's cometary origin still possible. More recently, Andreev (1990) calculated a range of Tunguska's possible heliocentric orbits and concluded that the most likely orbit is an Apollo-type one, in agreement with the result in Paper 1. The potential for constraining the object's orbital orientation is far from having been exhausted and the issue is further examined in this section.

The azimuth determinations of the Tunguska fireball's apparent radiant have an interesting history. There have been essentially three categories of approach used, based, respectively, on the pattern of forest devastation, on eyewitness accounts, and on modelling the ballistic wave. The early results yielded by these techniques were published in the 1960s and 1970s. They are summarized in Paper 1. The derived azimuths, in the range from 104° to 115°, led to my adoption of their characteristic average of 110° in Paper 1, which is one of the two values of the radiant azimuth used again below.

More recent investigations followed two of the three avenues of study, the eyewitness accounts and the extent of forest devastation. In their updated analysis of eyewitness accounts, Zotkin and Chigorin (1991) admit considerable discrepancies among the reports from the individual sources. They conclude that an azimuth of 126° yields the best match, with a formal 1-σ uncertainty of $\pm 12°$; another approach employed by them gives $120° \pm 20°$. On the other hand, a major progress achieved in the past two decades in mapping the butterfly-shaped region of the devastated forest (Fast *et* al. 1976, 1983) has led to an azimuth of 99° for the line of axial symmetry, with a 1-σ error estimated at significantly less than 10°. Thus, a second "standard" value that is adopted for the radiant azimuth in this paper is 100°. The remaining two parameters, the radiant elevation and the object's preatmospheric velocity, are known poorly and can only be used as softer constraints. The radiant elevation should be restricted to a range between 5° and 30°, as discussed in Sec. 6.

For a given azimuth of the apparent radiant, the full range of solutions that are allowed for the Tunguska heliocentric orbit can readily be examined in a plot of two orbital elements, the argument of perihelion ω and the orbital inclination i. For the two values of the azimuth of the apparent radiant, Fig. 1 shows the allowed (ω, i) combinations as functions of the aphelion distance, which is related to the preatmospheric velocity, and the radiant elevation. It is noted that the dark-shaded area of allowed "cometary" solutions (for which aphelia are beyond 4 AU) is much more restricted than the light-shaded area of allowed "asteroidal" solutions (for which aphelia are less than 4 AU). This contrast is further enhanced considerably, when the areas of the solutions allowed for the Tunguska object are compared with the known cometary and asteroidal populations. These comparisons are presented in Figs. 2–6, which are plots of the orbital inclination i against the argument of perihelion ω, or $\omega + 180°$; hence, one does not distinguish between the perihelion point locations above or below the ecliptic. The short-period comets are taken from a recent catalogue by Marsden and Williams (1995), while the asteroid samples are those from the updated *Minor Planet Center* pages on the World Wide Web (Marsden 1996).

Figure 2 is a plot of all the short-period comets (of an orbital period less than 200 yr and regardless of their perihelion distance), whose orbital inclination is less than 50°. The objects observed at more than one return to the Sun are distinguished from single-apparition ones. The plot shows the well-known concentrations of these comets for the argument of perihelion near 180° and 360° (e.g., Porter 1963), an effect that is a product of gravitational capture by Jupiter. Values of the argument of perihelion near 90° and 270° are possible only for the Jupiter-family members of extremely low orbital inclinations and for comets whose aphelia are situated far beyond Jupiter's orbit (and whose orbital periods are therefore $\gg$6 yr). The overlaid areas of allowed cometary solutions for the Tunguska object clearly occupy the regions of the (ω, i) plot that contain very few short-period comets. The only known comets whose locations on the plot are marginally consistent with either of the two allowed cometary solutions under consideration or with intermediate solutions (for which $100° < A_R < 110°$ and which are not plotted) are 24P/Schaumasse, 64P/Swift-Gehrels, 66P/du Toit, 89P/Russell 2, and 93P/Lovas 1. Their perihelion distances are between 1.2 AU and 2.3 AU and all are irrelevant as potential terrestrial impactors. The obvious conclusion is that the (ω, i) pairs consistent with the cometary solutions allowed for the Tunguska object are not typical for comets.

Figure 3 is a more restricted sample of short-period comets, containing only the objects with a perihelion distance of less than 1.2 AU, with an orbital period of less than 30 yr, and with an inclination of less than 40°. The characteristic dependence of i on ω is expressed even more prominently than in Fig. 2 and is seen to follow closely the relationship between the two orbital elements, dictated for the motion of Encke's comet by the Jovian secular perturbations over a period of 3400 yr (Brouwer 1947). On this plot, the two areas of the allowed cometary solutions are situated entirely outside the boundaries of the region populated by the relevant short-period comets. This lack of correspondence is strong evidence against cometary origin of the Tunguska object.

A very different scenario is presented when the areas of allowed asteroidal solutions for the Tunguska object are compared with the populations of Earth-approaching asteroids. Figure 4 compares the (ω, i) combinations implied by such Tunguska solutions with the known Apollo asteroids whose orbital inclinations are smaller than 50°. It is noticed that, contrary to the sample of the short-period comets, the (ω, i) distribution of the Apollo asteroids has gaps when the argument of perihelion is near 180° and 360°, but that there is an abundance of the Apollos, especially at inclinations $i < 25°$, for the intermediate values of ω, in particular near 90° and 270°, where comets are seldom found.

The orbital elements of as many as four dozen (!) objects fit in Fig. 4 the areas of Tunguska's allowed asteroidal solutions. In fact, the areas correspond to some of the heaviest concentrations on the (ω, i) plot. From Fig. 5 one can see that even a few Aten asteroids satisfy the constraints, even though they are rare altogether.

The most relevant sample of objects to examine for a correspondence with the areas of Tunguska's allowed asteroidal solutions is that of the *potentially hazardous asteroids* (PHAs), defined by Marsden (1996) as the objects whose minimum possible distance from the Earth's orbit does not exceed 0.05 AU. The (ω, i) distribution of 89 larger PHAs is presented in Fig. 6. The results of this set's comparison with the areas of allowed asteroidal solutions for Tunguska are similar to the results derived from the sample of the Apollo asteroids (Fig. 4). About three dozen of the PHAs satisfy the constraints, thus providing strong evidence that the Tunguska object was indeed one of these interlopers that in 1908 became deadly, rather than merely potentially perilous.

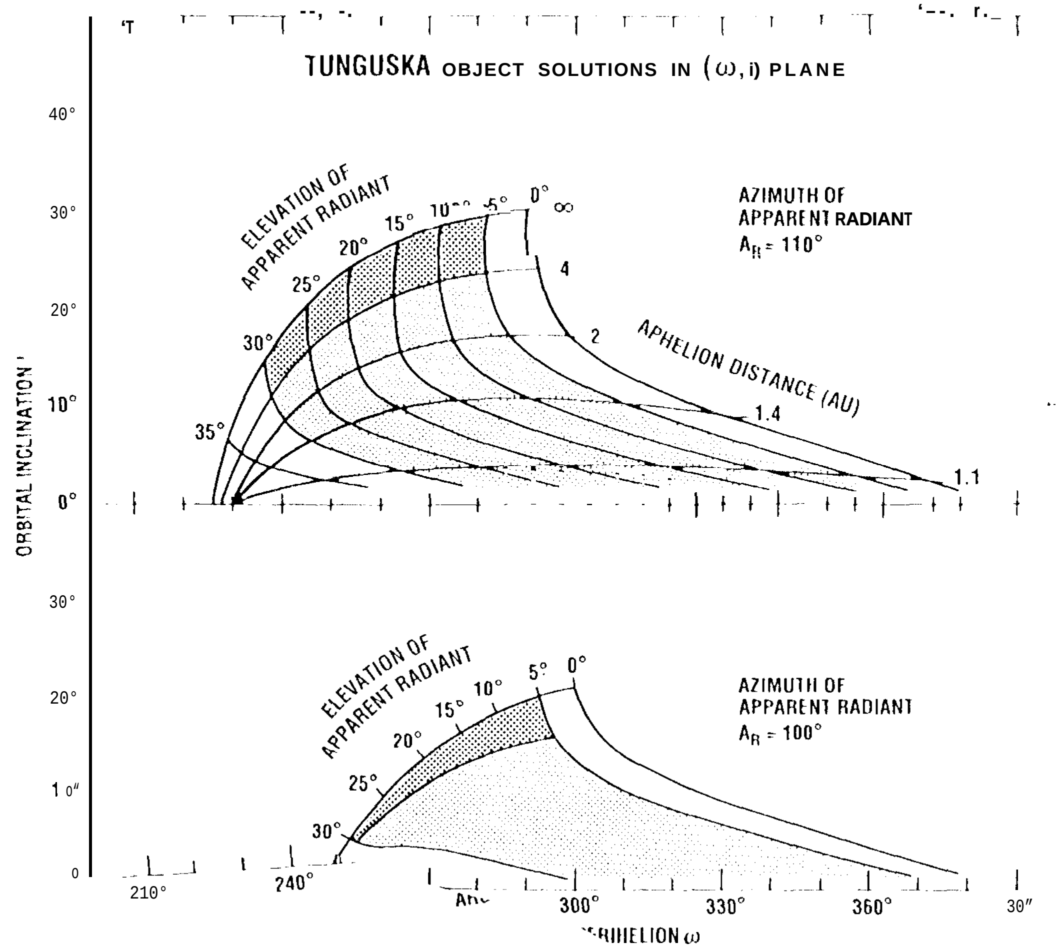

Fig. 1. Allowed combinations of the argument of perihelion ω and the inclination i of the heliocentric orbit of the Tunguska object as functions of the elevation of the fireball's apparent radiant and the object's aphelion distance. Upper panel: the area of the allowed solutions for the azimuth of the apparent radiant of 110°. Lower panel: the area of the allowed solutions (with abbreviated captions) for the azimuth of 100°. The heavily shaded areas refer to the allowed solutions assuming cometary nature of the Tunguska object (aphelion beyond 4 AU), the lightly shaded areas relate to the allowed solutions assuming asteroidal nature (aphelion within 4 AU). The elevation of the apparent radiant is in either case constrained to values between 5° and 30°.

6. The apparent radiant elevation

The constraints developed in Sec. 5 for the orientation of the heliocentric orbit of the Tunguska object were shown to be relatively sensitive to soft constraints in the elevation of the apparent radiant, which is the issue discussed in this section.

Values for the Tunguska's radiant elevation of not more than 30° have recently been advocated by Levin and Bronshten (1986), by Zotkin and Chigorin (1991), and by Bronshten (1994), among others. Only Korobeinikov *et al.* (1992) continue to prefer a radiant elevation of 40°.

It is important to emphasize that if the trajectory of the Tunguska fireball were relatively steep, the detection area for optical phenomena during atmospheric flight would have been severely restricted and its apparent prominence at locations up- and downrange its trajectory relative to the epicenter would not be as striking as the eyewitness accounts indicate. This is so because no fireball can attract one's attention in broad daylight before it reaches attitudes that are *substantially lower* than 100 km. Detailed quantitative arguments for this obvious conclusion have been discussed in Paper 1. Hence, if one is determined to dismiss a low-elevation trajectory, both the boundary of the area of luminous phenomena on Krinov's (1960) map and numerous *early* eyewitness accounts of the sightings (most of them from 1908) summarized by Krinov (1966) must be dismissed. These include three mutually consistent reports from the village of Nizhne-Ilimsk and a summary of eyewitness accounts collected by the director of a meteorological station at Kirensk, about 500 km to the southeast of the epicenter. They all date from July 1908, as does a report of "quite reliable information that ... in Vitim and up the Lena as far as Ust'-Kut many people . . . saw the pillar of fire" (Krinov 1966, pp. 156–161); all these locations are in the general directions from

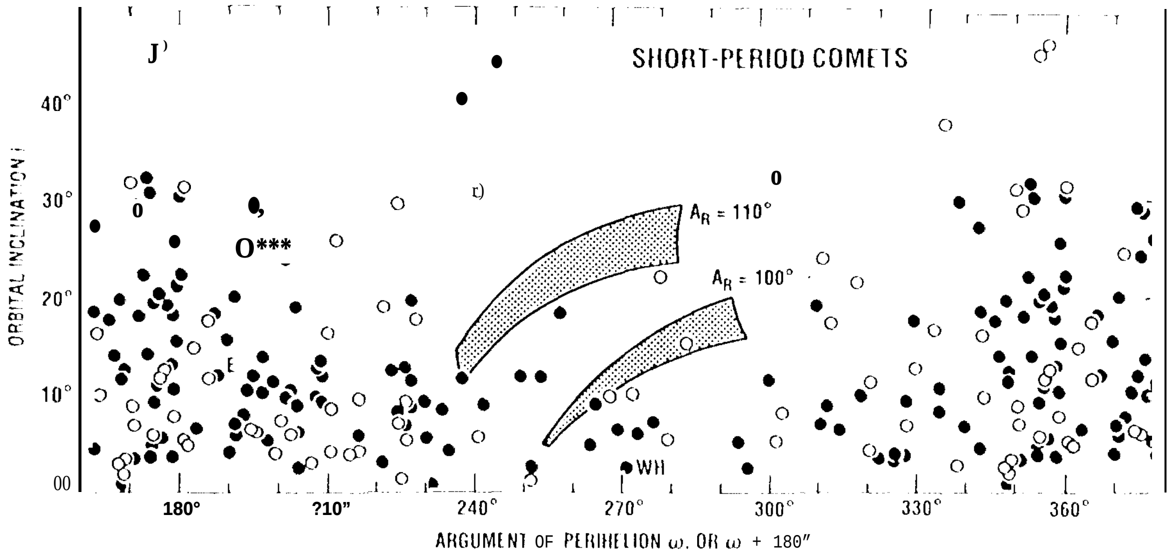

Fig. 2. Distribution of the argument of perihelion ω (or $\omega+180°$) versus the orbital inclination i for all the short-period comets whose $i < 50°$, with the overlaid distributions of cometary solutions (aphelion distances exceeding 4 AU) that are allowed for the Tunguska object on the assumption that the radiant azimuth is 100° or 110°. The open circles refer to single-apparition comets, the solid circles to comets of more than one apparition. Identified are P/Encke (E) and P/Wilson-Harrington (WH), the latter being a possible Amor asteroid. It is noticed that the Tunguska's cometary solutions occupy areas of the plot that are generally avoided by the short-period comets

the south-southeast to the east of the epicenter and more than 450 km from it. On the other hand, Krinov explicitly states that no sightings whatsoever were reported from Boykit, about 300 km to the west-northwest of the epicenter, in spite of the cloudless sky.

I am unaware of any case of demanding in the literature that the most compelling part of the eyewitness-account database compiled by Krinov (1966) be refuted. Yet, this is precisely what is implied by the critics of the fireball's low-elevation trajectory. Unless all the relevant eyewitness accounts are disregarded, there is no escape from the conclusion that the Tunguska's radiant elevation could under no circumstances exceed 30° and, almost certainly, not even 15°. More specifically, if the detection at Vitim and the nondetection at Boykit are taken at face value, the radiant elevation should still be lower than 15° and quite possibly as low as 5°, as advocated in Paper I.

7. Summary, comparisons, and conclusions

The following arguments, presented in Paper I and in this paper, its expansion, strongly support the notion that the Tunguska object was a small stony or carbonaceous asteroid and *not* a comet fragment:

(i) its explosion at an altitude of 8 km is analogous to, though more energetic than, the terminal flares of type II fireballs observed photographically at greater altitudes by the European Network and the Prairie Network;

(ii) the critical aerodynamic pressure at the point of explosion, estimated at ~200 bars, is consistent with a value that is expected from the extrapolation of the data on exploding type II fireballs to a mass of 10^{12}–10^{13} g; if the object were cometary, the critical pressure would be ~2000 bars, entirely out of a plausible range for fragile cometary material;

(iii) the pre-explosion velocity is derived to be slightly less than 10 km/s, consistent with independent determinations based on an interpretation of the seismic observations and on a laboratory simulation of the uprooted forest;

(iv) because an object of Tunguska's size cannot be efficiently decelerated by the Earth's atmosphere, the initial, preatmospheric velocity could not have been higher than the terminal velocity by more than several km/s and could have only marginally exceeded the Earth's velocity of escape, thus ruling out a comet-like orbit of moderate to high eccentricity;

(v) existing limited evidence on the Tunguska event is inconsistent with a fragmentation pattern typical for cometary fireballs; compared with more compact stony impactors, fragmentation distinctly precedes deceleration for comet impactors, whose propensity to fragmentation, expressed quantitatively by their high effective ablation coefficients, may in fact increase with increasing dimensions; a comet impactor with the residual mass of Tunguska at the time of terminal explosion would have had an entry mass of at least a few times 10^{13} g (about one order of magnitude greater than a stony impactor of the same residual mass), would have begun to disintegrate precipitously at high altitudes, near 70–80 km above sea level,

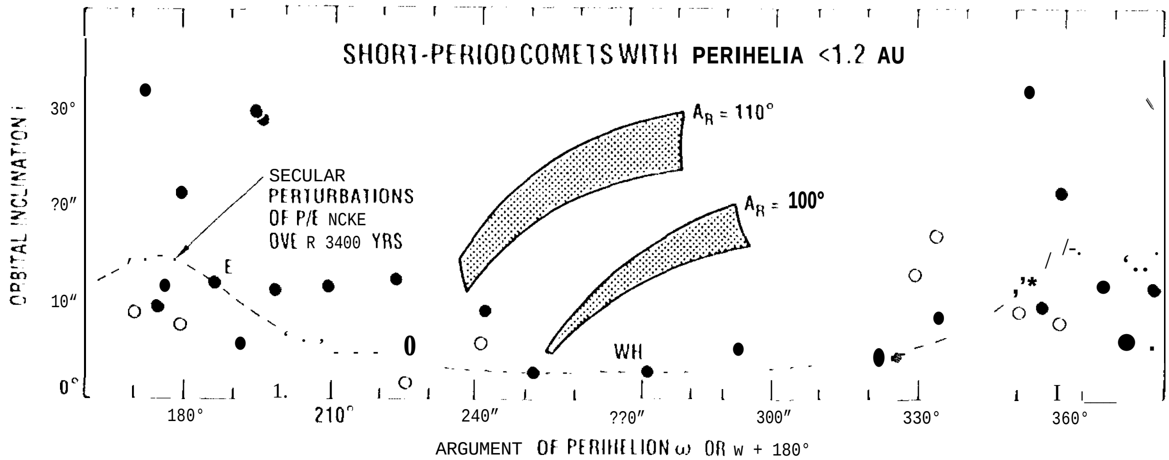

Fig. 3. Distribution of the argument of perihelion ω (or ω+180°) versus the orbital inclination i for the short-period comets with perihelia smaller than 1.2 AU, with orbital periods less than 30 yr, and with i <40°, and its comparison with the overlaid distributions of cometary solutions (aphelion distances exceeding 4 AU) that are allowed for the Tunguska object on the assumption that the radiant azimuth is 100° or 110°. The open circles refer to single-apparition comets, the solid circles to comets of more than one apparition. Identified are P/Encke (E) and P/Wilson-Harrington (WH), the latter being a possible Amor asteroid. Also plotted is the curve of the (ω, i) pairs described by the orbit of P/Encke due to the Jovian secular perturbations during a cycle of **3400** yr. It is noticed that the Tunguska's cometary solutions occupy areas of the plot that are populated by no Earth-approaching short-period comets.

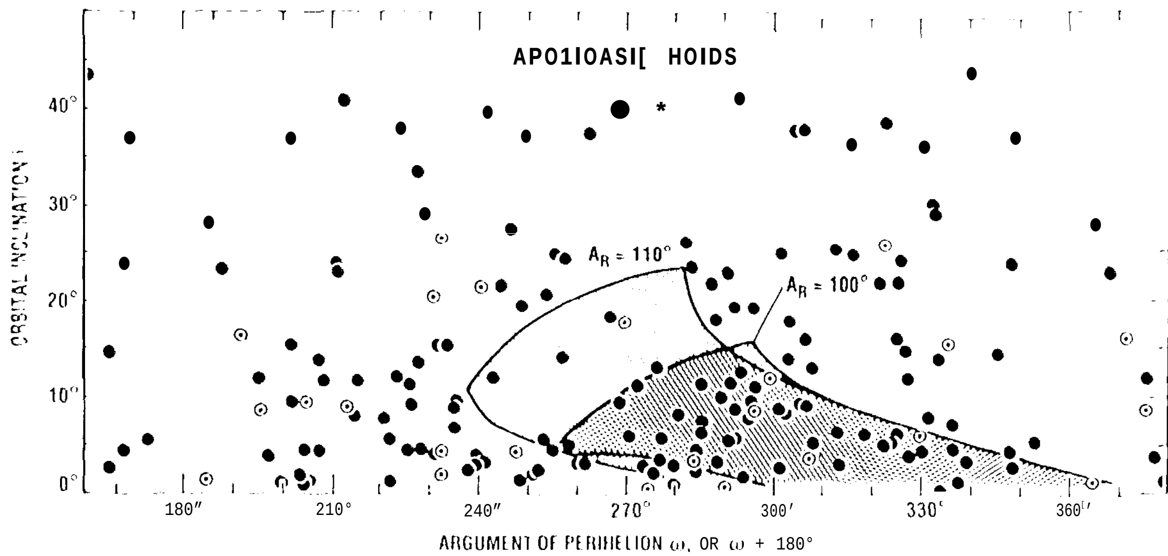

Fig. 4. Distribution of the argument of perihelion ω (or ω+180°) versus the orbital inclination i for the Apollo asteroids with i < 50° and its comparison with the overlaid distributions of asteroidal solutions (aphelion distances less than 4 AU) that are allowed for the Tunguska object on the assumption that the radiant azimuth is 100° or 110°. The dotted circles refer to objects whose aphelia are beyond 4 AU, while the solid circles are asteroids with aphelia less than 4 AU from the Sun. It is noticed that the Tunguska's asteroidal solutions occupy areas of the plot that are densely populated by the Apollo asteroids.

and would have experienced a series of major outbursts during its atmospheric flight, contaminating the Earth's atmosphere with immense amounts of microscopic dust and causing severe extinction effects of a magnitude approaching a global catastrophe;

(vi) a comet event of such a magnitude would have been extremely rare, perhaps 10 100 times more so than an asteroidal one of the same explosion energy, making the object's cometary origin highly unlikely from a statistical standpoint as well;

(vii) the Tunguska object's limited orbital evidence is also unfavorable to cometary nature of the impactor; allowed solutions for its heliocentric motion immediately prior to the encounter are found to be consistent with the

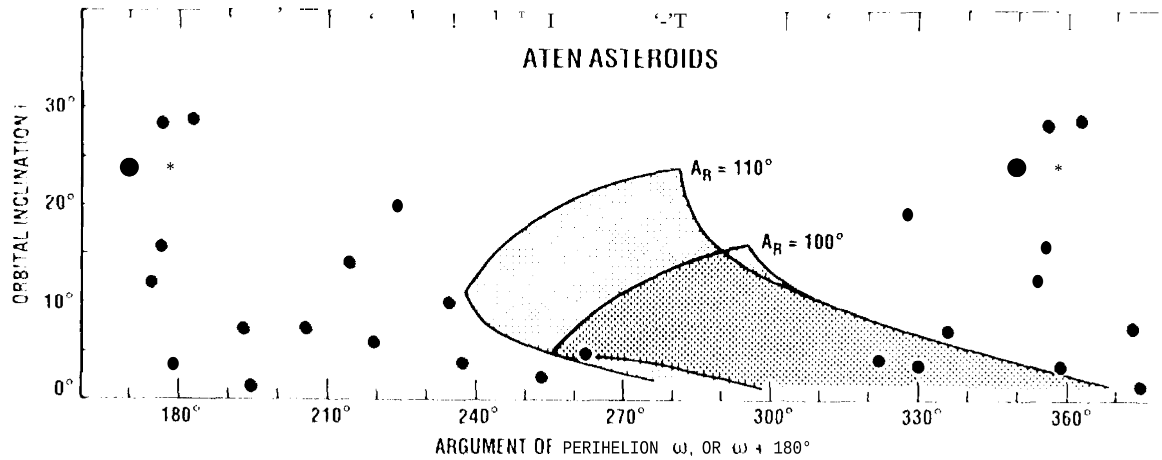

Fig. 5. Distribution of the argument of perihelion ω (or $\omega+180°$) versus the orbital inclination i for the Aten asteroids with $i<40°$ and its comparison with the overlaid distributions of asteroidal solutions (aphelion distances less than 4 AU) that are allowed for the Tunguska object on the assumption that the radiant azimuth is 100° or 110°. Even though the total number of these asteroids is small, it is noticed that the Tunguska's asteroidal solutions occupy areas of the plot where a few of the Atens are located.

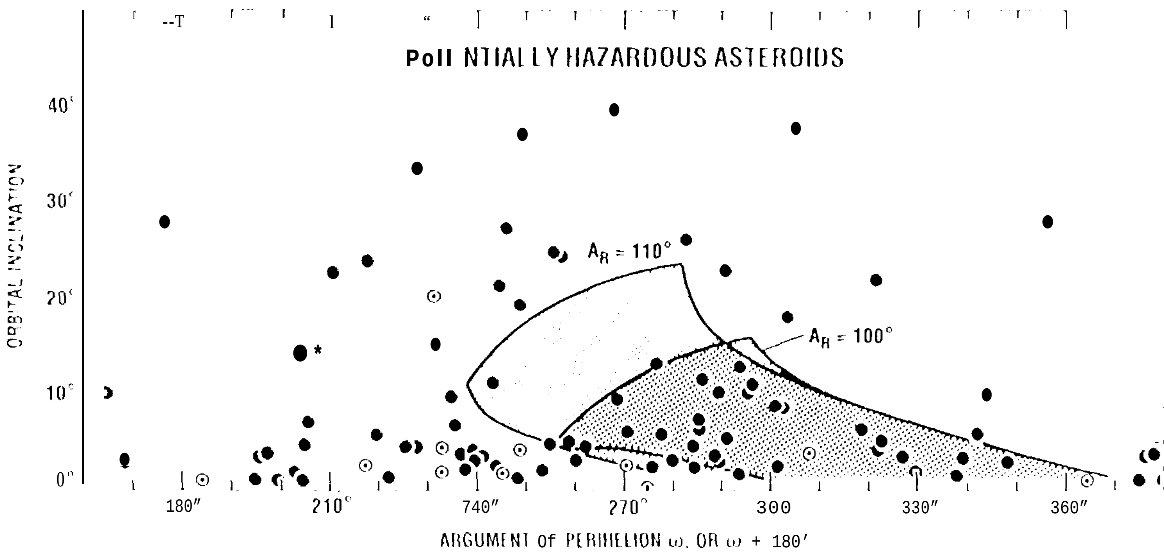

Fig. 6. Distribution of the argument of perihelion ω (or $\omega+180°$) versus the orbital inclination i for the potentially hazardous asteroids (with minimum possible distance from the Earth's orbit of not more than 0.05 AU) whose $i<50°$ and its comparison with the overlaid distributions of asteroidal solutions (aphelion distances less than 4 AU) that are allowed for the Tunguska object on the assumption that the radiant azimuth is 100° or 110°. The dotted circles are objects with aphelia beyond 4 AU, while the solid circles are asteroids with aphelia less than 4 AU from the Sun. It is noticed that the Tunguska solutions occupy some of the areas of the plot that are densely populated by the potentially hazardous asteroids, strongly implying that the Tunguska object was in fact one of them.

orbital distribution of the Earth-crossing asteroids but not with the orbital distribution of the short-period comets;

(viii) orbital information is particularly unfavorable to the hypothesis on the association of the Tunguska object with Encke's comet; it was shown in Paper 1 that the nodal line has to be rotated by 56° in order to make the collision with the Earth possible, a dynamically unacceptable proposition that fails to satisfy the necessary conditions of orbital similarity and places no plausible limits on the time scale needed for such a large planetary-perturbation effect.

It is now appropriate to set the author's arguments in the context of the history and evolution of ideas on the Tunguska object. Kulik's (1926) early conclusion was influenced by the entirely fortuitous coincidence between the timing of the fall and the subsequent "light nights" over much of Euroasia on the one hand and the Earth's transit across the orbital plane of the approaching comet Pons Winnecke on the other hand. Other proponents of a cometary hypothesis were Whipple (1930), who argued that the light nights in the aftermath of the fall had been caused by the Tunguska's dust tail; Astapovich (1933), who concluded that the object had moved in a hyperbolic heliocentric orbit; and Vernadsky (1941), who suggested that the impactor had been a dense cloud of cosmic dust, thus introducing a paradigm that was consistent with the then popular sand-bank model for cometary nuclei. In one of his last papers, Kulik (1939), still convinced that large fragments of the body impacted the ground, expressed the opinion that the Tunguska object was an iron meteorite, as all meteorites more massive than 500 kg were made of iron. Since he never refuted his earlier notion of the object's cometary nature, one should assume that Kulik did not consider Tunguska's cometary origin and the iron composition of its large fragments as mutually exclusive.

For at least seventy years after the Tunguska fall, the belief that the object was of cometary origin clearly dominated the literature, with Krinov (1949, 1966), Fesenkov (1961, 1966, 1969), and Kresák (1978), to name a few, among the strongest supporters of this hypothesis. Early attempts to introduce effects of atmospheric fragmentation into meteor equations helped in fact to strengthen the prevailing opinion that favored cometary nature of the Tunguska object. This was, for example, the case of Grigoryan's model (1976, 1979). But after evaporation effects, neglected in the original paradigm, were accounted for (Bronshten 1994), the computed upper limit to the altitude of complete disintegration (i. e., the altitude of explosion) came out to be fairly insensitive both to the impactor's bulk density and to its strength. Unfortunately, these calculations were carried out only for an assumed preatmospheric velocity of 33 km/s and could not therefore discriminate between the two hypotheses.

I have been unable to find any paper before 1983, in which cometary origin would have been criticized as unacceptable. To my knowledge, Baldwin (1963) came close to this conclusion, when on p. 40 of his book he said that "the description of the amount of dust resembles the effects observed when a great stony meteorite arrives . . . ", but on p. 43 he conceded that it was "entirely possible that the object was composed largely of ices, in conformity with Whipple's concept of comet heads." Baldwin was convinced that comets "must contain a certain amount of rocky material."

The balance between comet and asteroidal hypotheses began to change rather suddenly in 1983. Virtually at the same time as my very definite conclusion on the object's nature was published in Paper 1, a compositional study by Ganapathy (1983) appeared, in which the author examined submillimeter-sized metallic spheres from the site of fall and concluded that the object may have been a stony meteorite. Although Ganapathy's findings on Tunguska's contribution to the iridium infall at the South Pole were not confirmed by Rocchia *et al.* (1990), his results are not necessarily nullified in their entirety. In the least, they suggest that asteroidal and cometary origins of the object are equally plausible. Also at about this time the issue of cosmic bombardment of the Earth was reviewed by Shoemaker (1983), who pointed out that the failure of the Tunguska object to reach the ground only showed that it was not a large iron meteorite or stony iron; thus, Shoemaker did not exclude the possibility of a stony or carbonaceous asteroid either.

While in the 1980s the hypothesis of Tunguska's cometary nature continued to enjoy some popularity (e. g., Clube and Napier 1984, Levin and Bronshten 1986), a number of independent investigations completed in the early 1990s already shifted the emphasis to asteroids. Pr-err) his orbital study, Andreev (1990) concluded that an Apollo-type orbit is the most likely one for the Tunguska object. Three years later, the importance of atmospheric fragmentation of massive impactors was emphasized and the highly discriminatory behavior of comets, carbonaceous asteroids, stony asteroids, and iron asteroids during their atmospheric flight was established in several investigations. Hills and Goda (1993) found from their model that a stony asteroid must be greater than 200 m across, much larger than the Tunguska object, to hit the ground. Chyba *et al.* (1993) developed a model, which essentially obeys the deceleration and ablation equations of a single-body paradigm and for which ablation is assumed to proceed only by evaporation until the dynamic pressure begins to exceed the object's yield strength. At this point, an effect of compressive deformation is introduced, thereby rapidly expanding the impactor's effective cross sectional area during the remaining part of its atmospheric flight. The authors showed that this model implies a sharp peak in the rate of energy deposition at the end of the atmospheric trajectory, which can be described as a terminal explosion. Its altitude depends on the impactor's entry mass, density, velocity, strength, composition, and trajectory angle. Applying this model to the Tunguska object, Chyba *et al.* (1993) found that its explosion at an altitude of about one scale height indicates that the impactor was an ordinary stone.

In the opinion of this author, the most realistic model for massive fireballs that has been proposed to date is that based on actual fitting to the observations of such objects. Especially illuminating descriptions of its properties are presented in two recent investigations, by Ceplecha *et al.* (1993) and by Borovička and Spurný (1996). One impressive aspect of this model is that it has already been successfully applied to almost 500 fireballs. The concept is based on the recognition that major losses of mass occur primarily during, or immediately subsequent to, discrete fragmentation events and in any case as their result. This model also accounts for quasi-continuous fragmentation along the entire atmospheric path, not only at low altitudes. The model was initially intended as a tool for analyzing photographically recorded fireballs, but both Ceplecha (1995) and Borovička and Spurný (1996) have shown that it also can be used with advantage for predictive purposes. Summarizing the results of these investigations, one can offer the following classification of atmospheric fragmentation of fireballs:

A. *quasi-continuous mode*,

B. *discrete-event mode*:

B.1. *bulk disruption* (*involving major fragments*),

B.2. *pulverization* (*involving predominantly microscopic debris*).

The contribution from the quasi-continuous mode can readily be described by an appropriate value of the ablation coefficient, as mentioned in Sec. 4. While both macroscopic and microscopic particulates are lost in this fragmentation mode, there is no need to distinguish between large-sized and small-sized debris, because of its continuing ablation across the entire size spectrum. In the discrete-event mode, however, the size characteristics of the major fragments are important and the analysis should proceed accordingly. The greatest value of Ceplecha *et al.*'s (1993) paper consists in the systematic examination of the B.1 mode of fragmentation, which these authors call *gross fragmentation* and which undoubtedly is of primary importance for stony and carbonaceous impactors, even though ablation effects of the two fragmentation modes cannot be separated from one another. For example, a common scenario is that of an impactor breaking up into several bulk pieces, each of which continues to ablate by fragmentation (as well as by evaporation and melting). Successful analysis of the B.2 fragmentation mode, which dominates the disintegration process of cometary impactors in the atmosphere, is one of the major contributions by Borovička and Spurný (1996), including their estimates for the amounts of microscopic and macroscopic debris involved in the discrete events and their formulation and application of a novel concept of destruction depth.

The hills Gods model was criticized by Ceplecha (1995), who appropriately pointed out that photographic observations clearly indicate that fireballs, even meteorite-generating fireballs, fragment at dynamic pressures on the order of 1 12 bars (e.g., Ceplecha 1961, McCrosky *et al.* 1971, Halliday *et al.* 1981), which are considerably lower than the strength of stony meteorites. Ceplecha also emphasized that if the model were correct, there would be no meteorite falls from objects initially several meters across, in obvious contradiction to gathered evidence.

Similar objections can also be raised to the model by Chyba *et al.* (1993). Indeed, as part of background information, Chyba (1993) plotted the calculated explosion altitude versus explosion energy, concluding that stony objects with explosion energies in the range of 1 kton to 1 Mton undergo an airburst at an altitude between 10 and 25 km; the lower end of this range includes meter-sized asteroidal objects – some of them known to have yielded meteorites which were observed by the European Network and the other fireball monitoring networks (Ceplecha 1994) as well as the recently recovered Peekskill meteorite (Brown *et al.* 1994, Beech *et al.* 1995). For massive fireballs whose fragmentation is not predominantly of the B.1 mode and whose atmospheric flight is not terminated by a meteorite fall, Chyba *et al.*'s (1993) approach can be remedied to some extent by applying, in the mass-loss equation, an "effective" ablation coefficient that accounts for integrated effects of fragmentation, evaporation, and melting. This refined approximation should be applicable with advantage especially to cometary impactors. Indeed, when employed by Sekanina (1993) to predict impact circumstances for the fragments of comet Shoemaker-Levy 9, the resulting terminal altitudes virtually coincided with the altitudes calculated subsequently by Borovička and Spurný (1996) from their model accounting for discrete-event fragmentation.

Even though there remain differences among the various fragmentation models for very massive fireballs, the recent developments clearly point to asteroidal nature of the Tunguska object, consistently with other presented evidence. However, one issue where I am not prepared to take sides at this time is whether the object was a normal stone or a carbonaceous chondrite. As mentioned above, the presence of a terminal explosion appears to suggest a fireball of type II, the category usually associated with carbonaceous chondritic material. However, this relationship still remains somewhat speculative. Borovička and Spurný (1996) point out, for example, that the Benešov fireball, one of the best examples of a type II fireball with a terminal flare, may have been an ordinary chondrite. It was already mentioned that Chyba *et al.* (1993) proposed that Tunguska was a stony object and that Ganapathy (1983) concluded from his compositional investigation of submillimeter-sized metallic spheres collected at the site of the Tunguska fall that the object may well have been a stony meteorite. More recently, evidence compatible with Tunguska being a normal density meteorite was presented by Longo *et al.* (1994) and by Serra *et al.* (1994), who extracted and analyzed microscopic particles trapped in the resin of surviving conifers at the site of the Tunguska fall. They showed from the growth rings of the trees that the time distribution of these particles had peaked in 1908 and identified 14 elements as probably coming from the Tunguska fragmented material.

In summary, I find the gathered evidence in favor of asteroidal origin of the Tunguska object very compelling, with its physical, compositional, and orbital aspects both mutually and self-consistent.

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